Surface Analysis of C-Mod tiles

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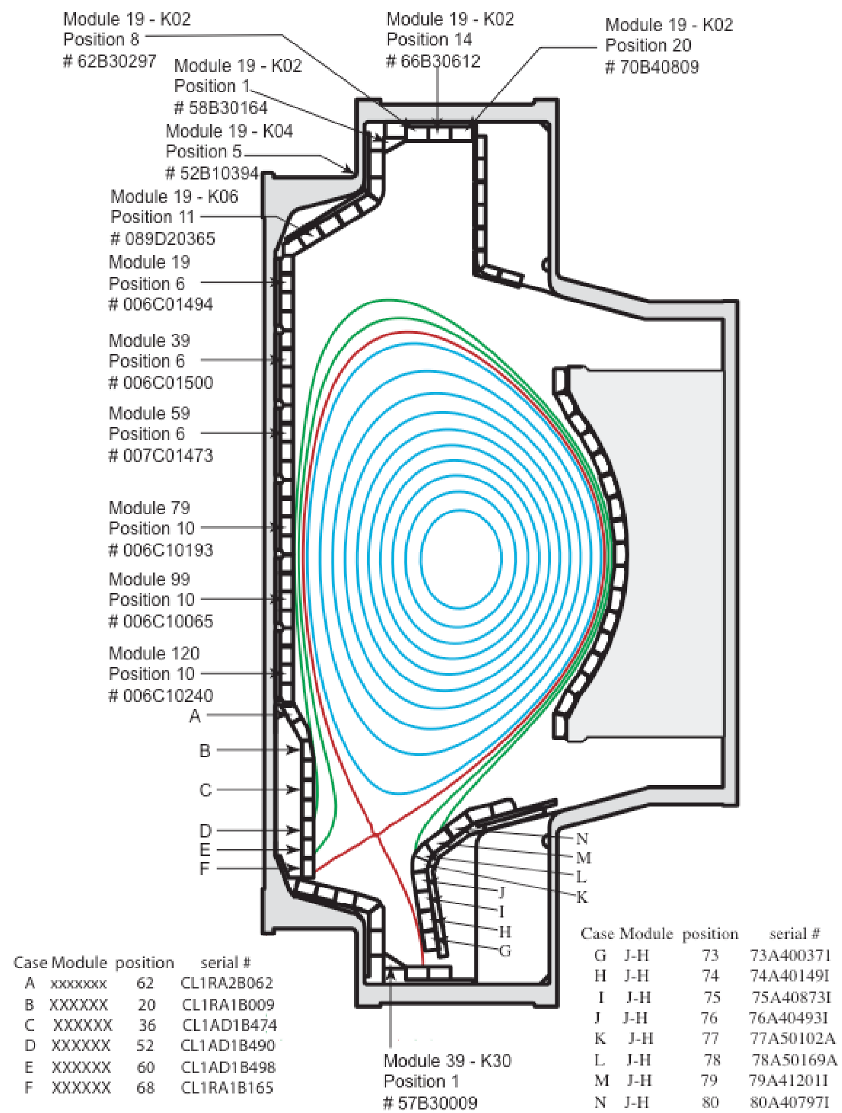
C-Mod tiles removed during 2004 summer vent. Ion beam analysis used for “archeological” study of erosion and H retention in the only all-metal tokamak.

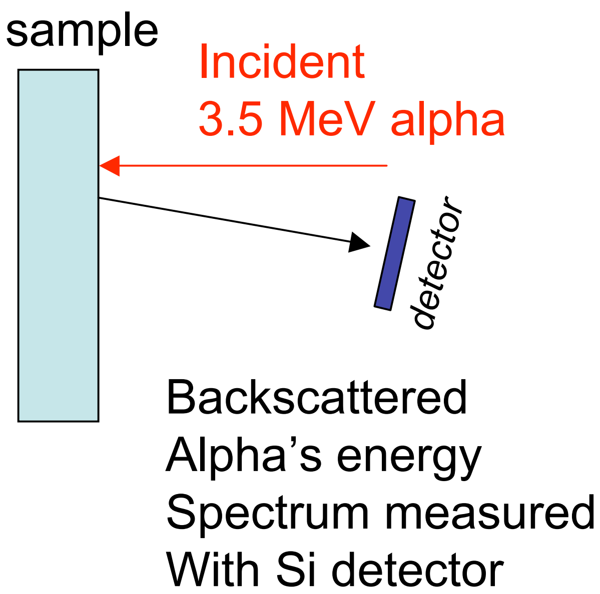
- Nearly full poloidal set of molybdenum tiles.

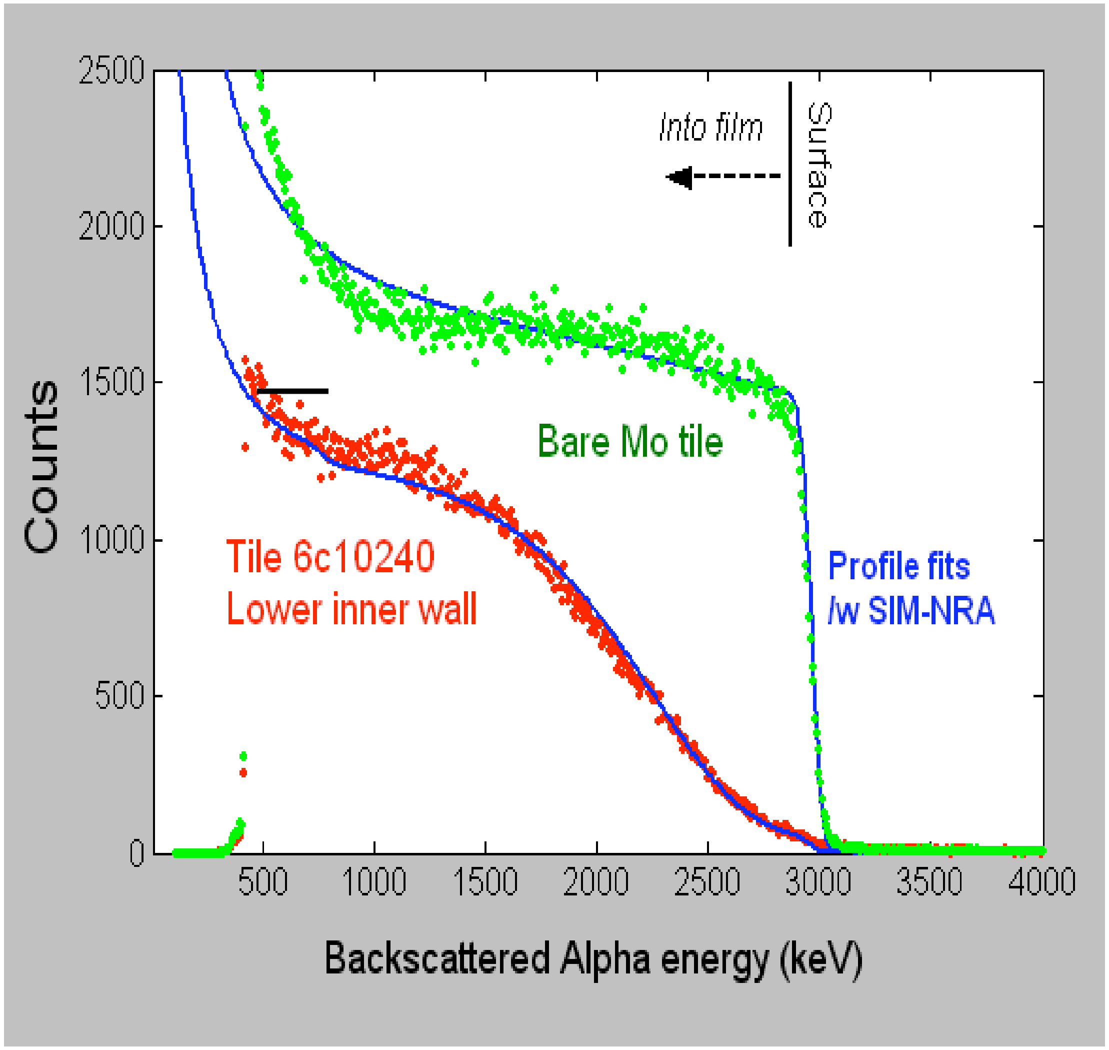
- What are we looking for?
  - Boron / Mo / O content
  - H / D fuel content.
  - Poloidal & depth pattern.

- Method: High energy (> 1 MeV) ion beam analysis at UW-Madison.
  - Non-destructive.
  - Element / isotope sensitive.
  - Depth profiles.

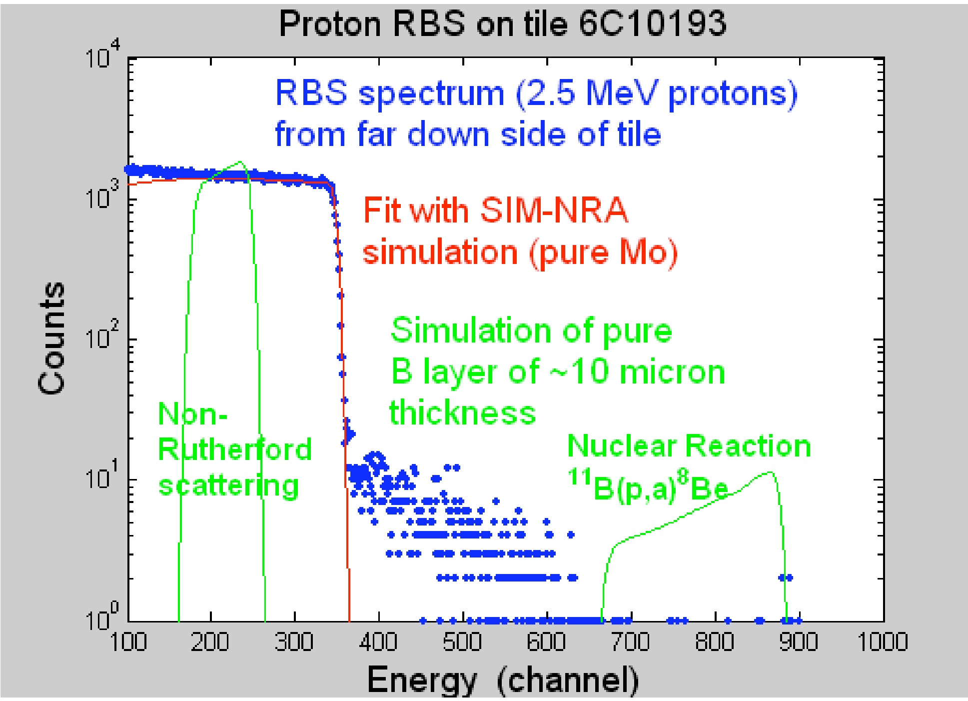


Ion beam analysis (IBA): Energy spectrum of scattered ions &/or nuclear reaction products describes elemental depth profiles in sample

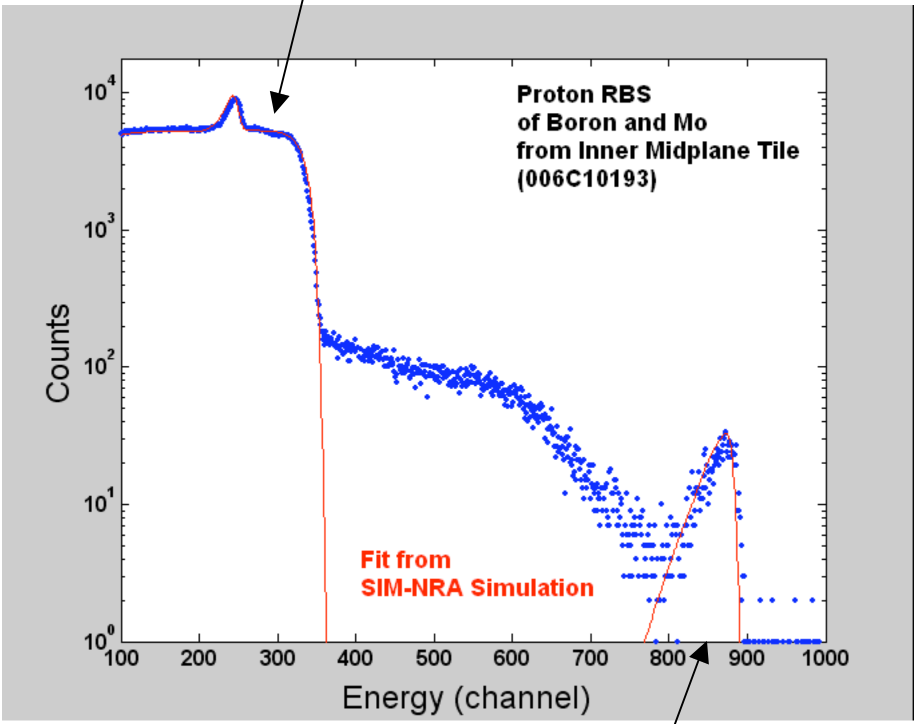




Two IBA techniques for B depth profiles in presence of Mo: Protons provide measurements ~20 microns into samples



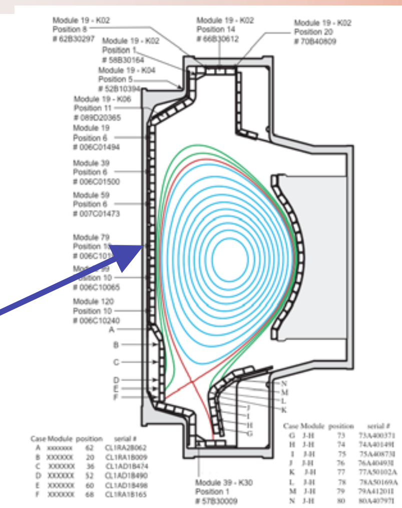
B / Mo / O profiles from RBS

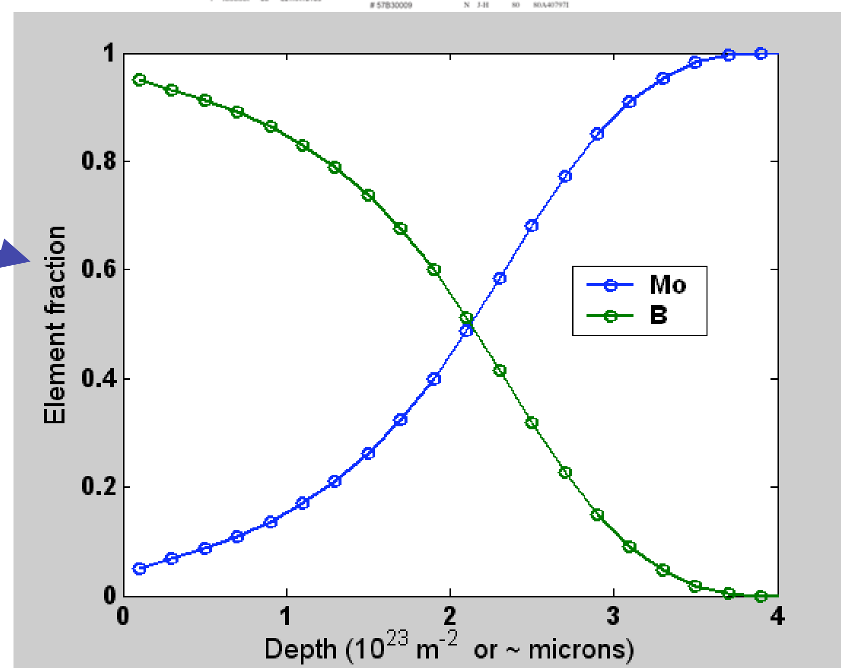


Near-surface B concentration From NRA

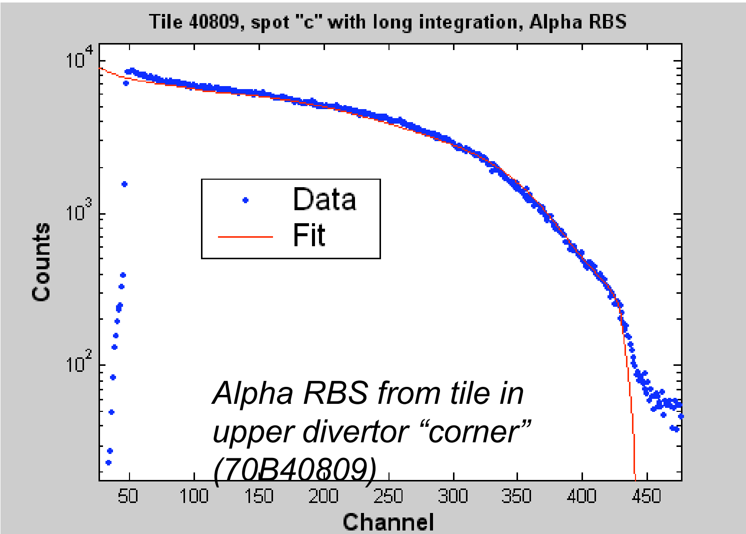
C-Mod tiles outside the divertor: Thick boron (> 2 microns) with a long and "diffuse" tail into the Mo substrate…but also Mo at surface ~1-5%

6C10193: Midplane centerpost

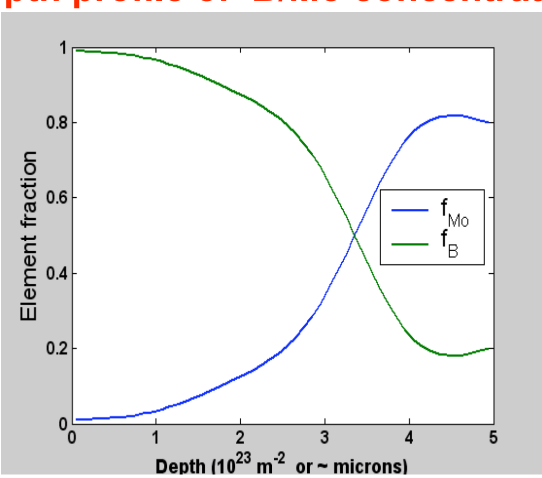




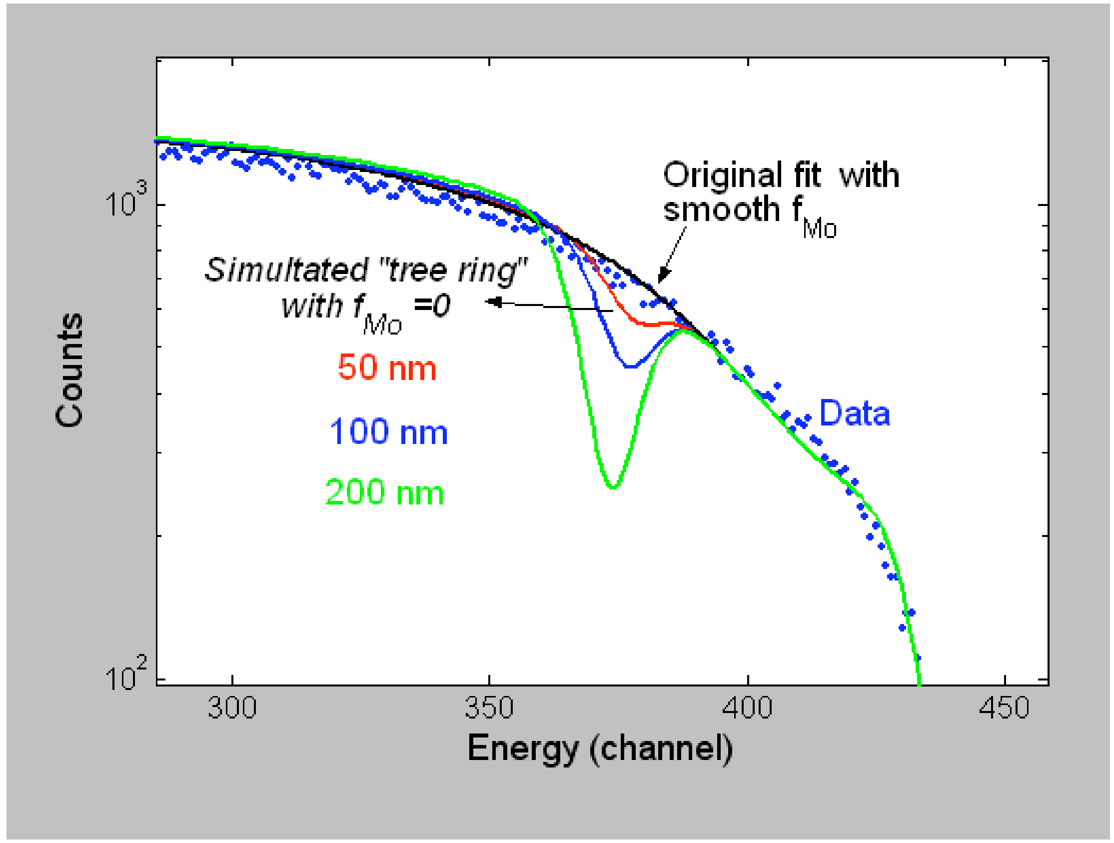
There is no evidence of discrete B film applications (i.e. tree-rings) expected from intermittent boronizations.



Depth profile of B/Mo concentration

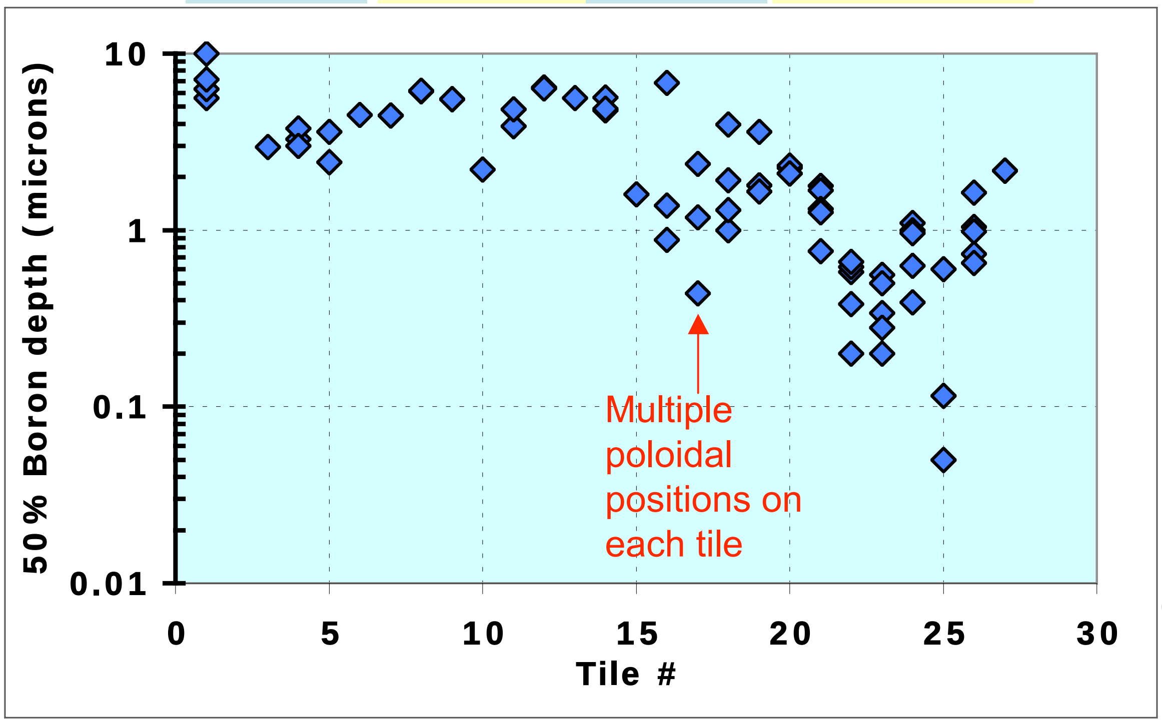


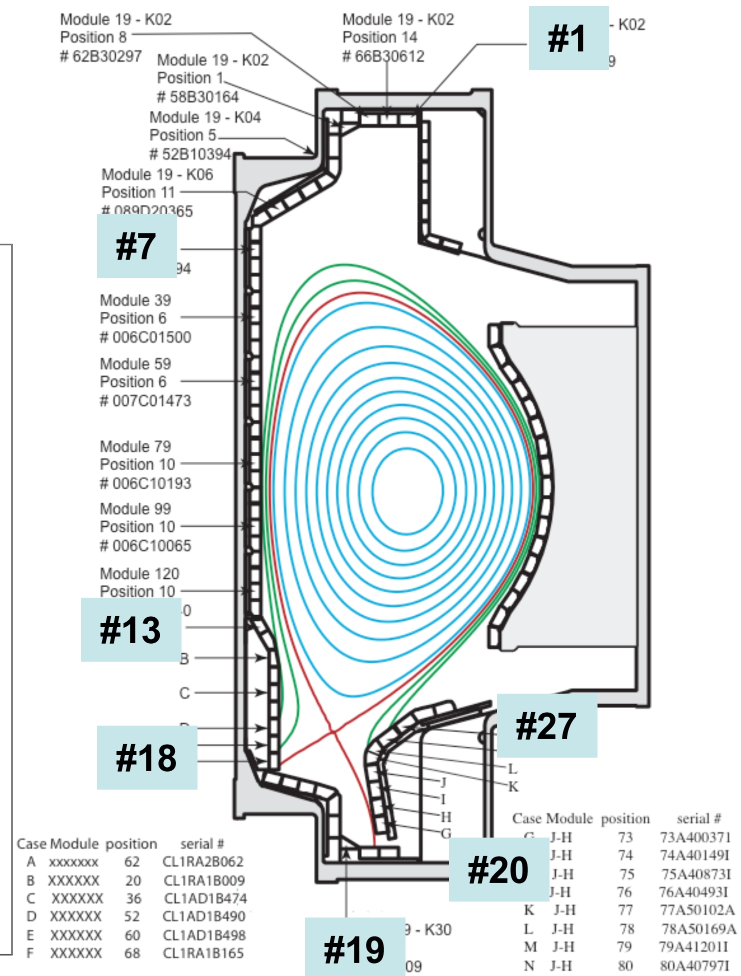
3.5 MeV Alpha RBS provides ~20 nm depth resolution



Poloidal distribution of B film thickness reveals erosion / deposition processes.

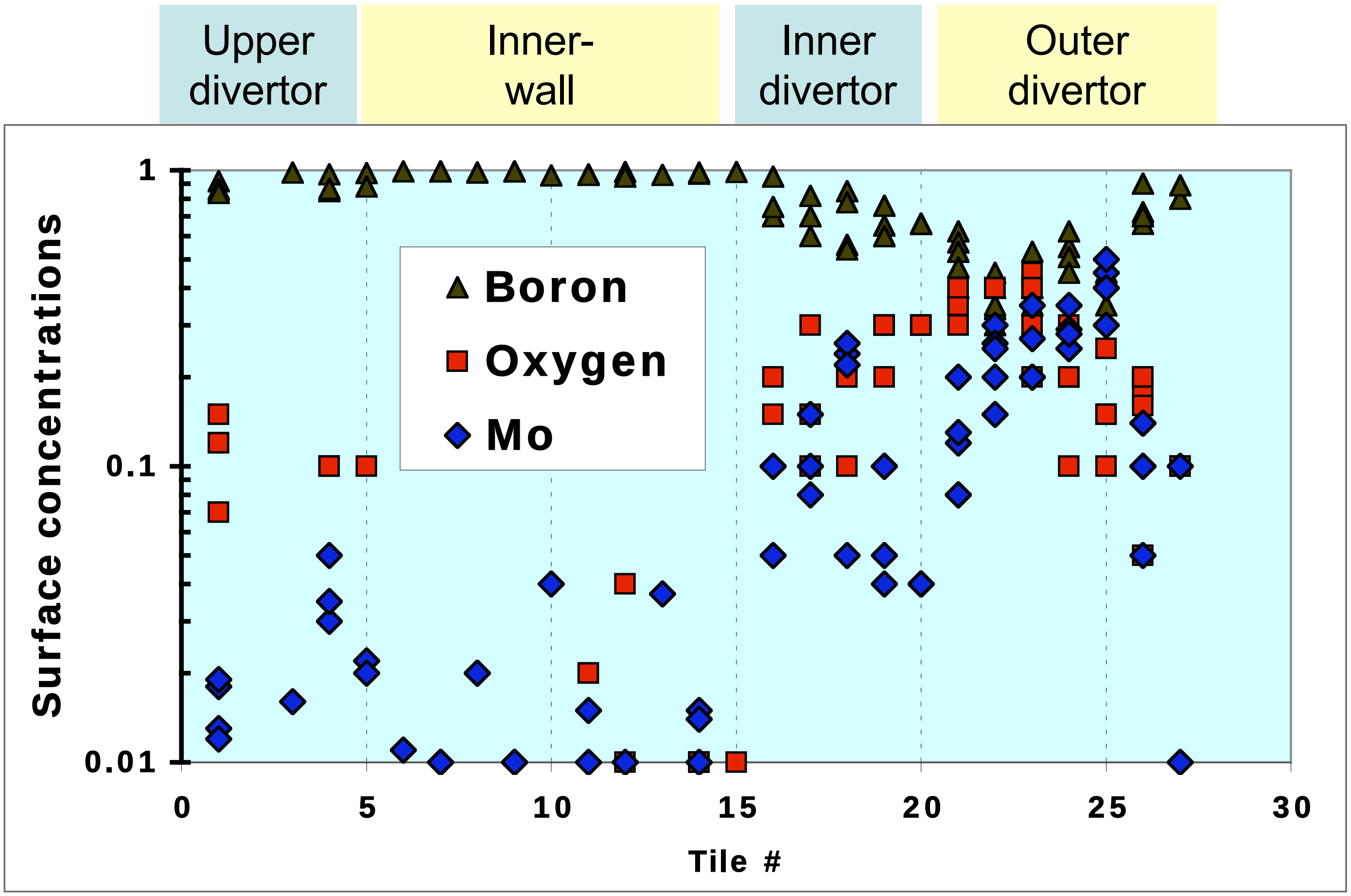
Process	??	*~40 x 100 nm boronization films*	*Plasma deposition*	*Plasma erosion*
Location	Upper divertor	Inner-wall	Inner divertor	Outer divertor



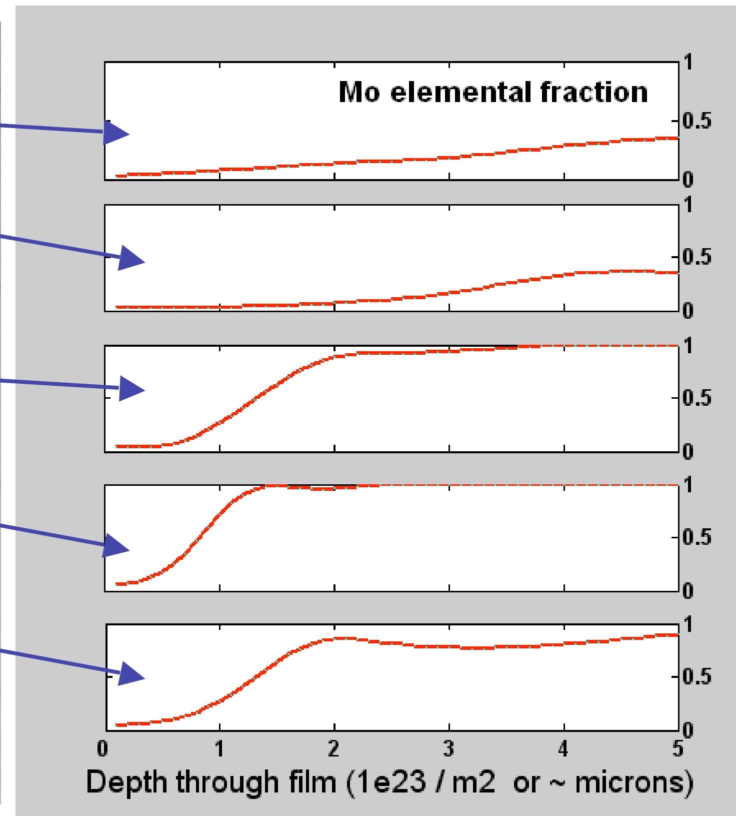


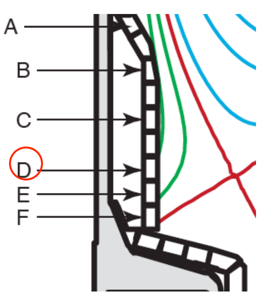
C-Mod plasma-facing surfaces are dominated by low-Z boron, not high-Z molybdenum, but both are available for erosion on all surfaces.

- Net erosion outer divertor still has B from plasma recycling.
- High oxygen content found in divertor regions with plasma erosion?
- Plasma deposits at inner divertor contain Mo.
- Complex picture of mixed Mo/B.



Inner divertor tile has toroidal “slopes” that determine Mo/B layer spatial pattern. Deposition arises from ion B deposition during discharges at an overall rate ~ 1 nm/s



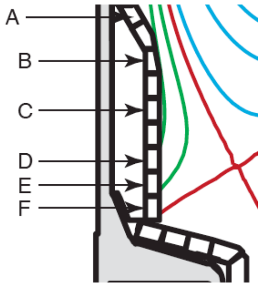


“D” Inner Strikepoint Tile

Alpha (3.5 MeV) RBS

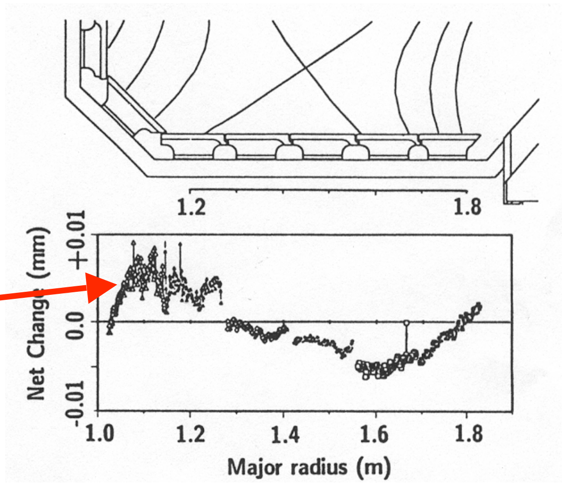
Inner divertor low-Z deposition consistent with C tokamaks. Boron deposition rate ~ 1 nm/s: larger than Mo net erosion rate at outer divertor but similar to carbon in DIII-D

"E" Tile ~ Inner Strikepoint.
Shadowed region:
$d_{B1/2}$ = 0.2 microns



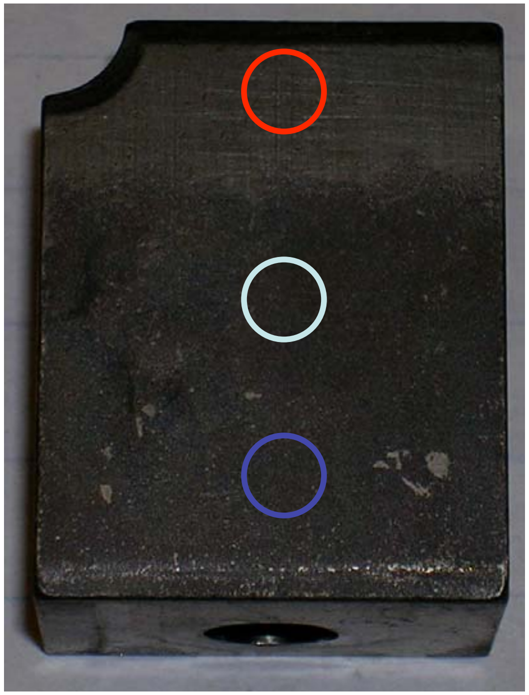
	C-Mod	DIII-D
PFC	B / Mo	C
Location	Inner div.	Inner Div.
Deposits	~ 3-5 μm	~3-6 μm
Δt	~4000 s	~4000 s
Inner div. deposition	~ 1 nm/s	~ 1nm/s
Outer div. erosion	~0.1 nm/s (Mo)	~1-3 nm/s (C)
Bzn. film	2.5 μm	0.5 μm

C erosion/deposition In DIII-D in one year

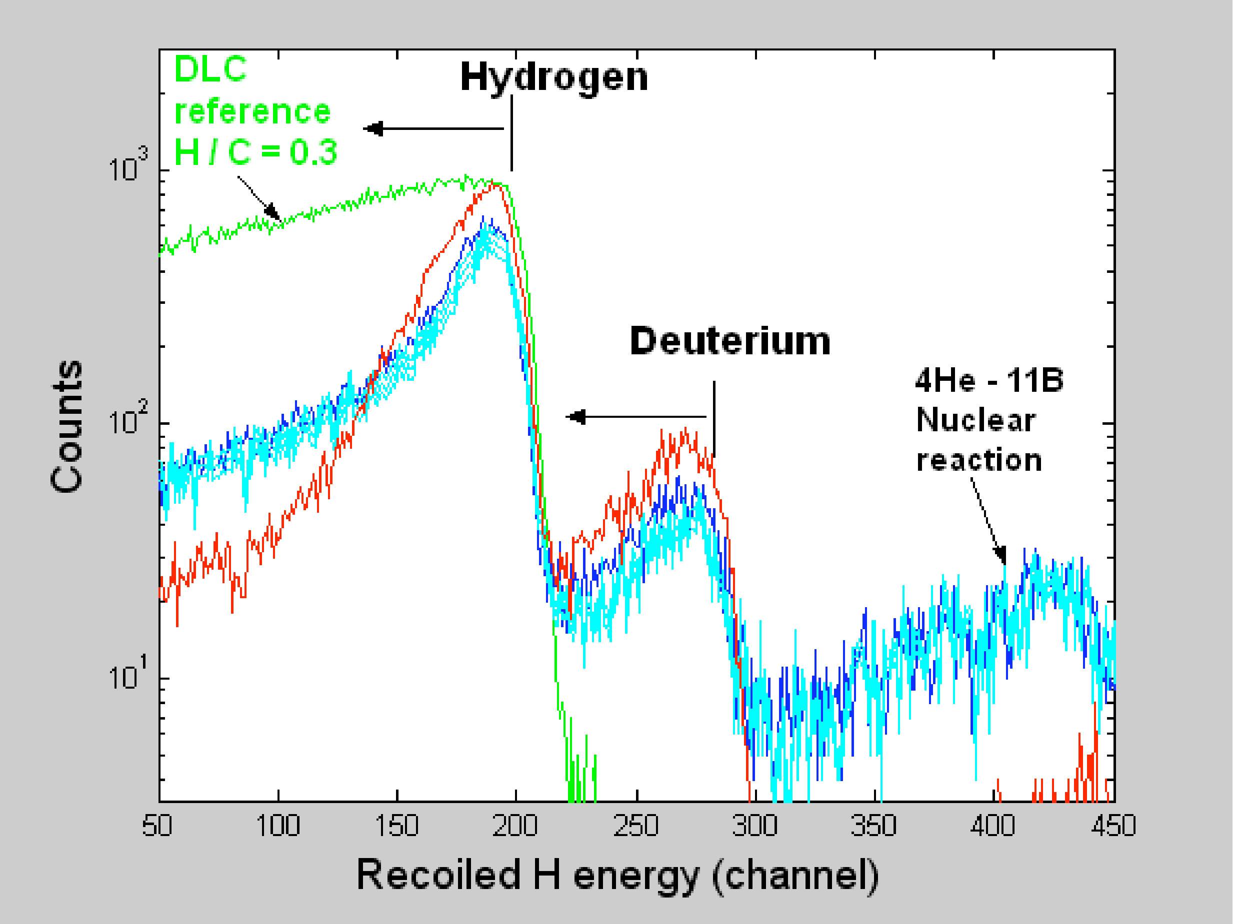


Elastic Recoil Detection (ERD) measures hydrogenic species.
Surface H similar to Diamond-Like Carbon film
Wiped regions still have significant surface D without boron.

Film "wiped" /w water



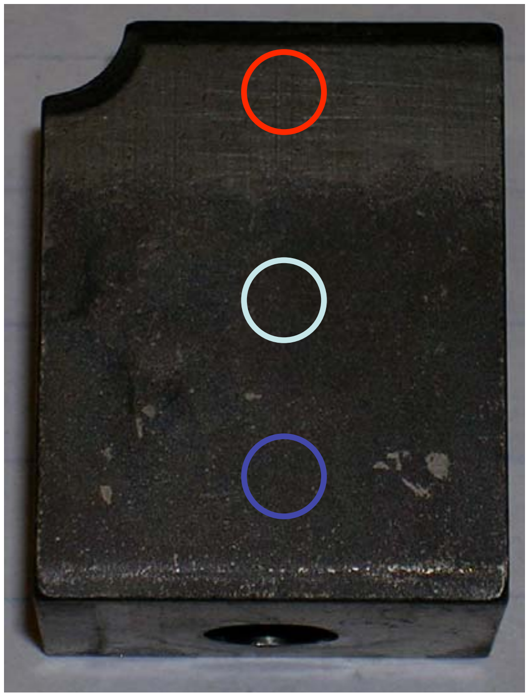
Tile 006C01500
Upper
Midplane at
Inner wall



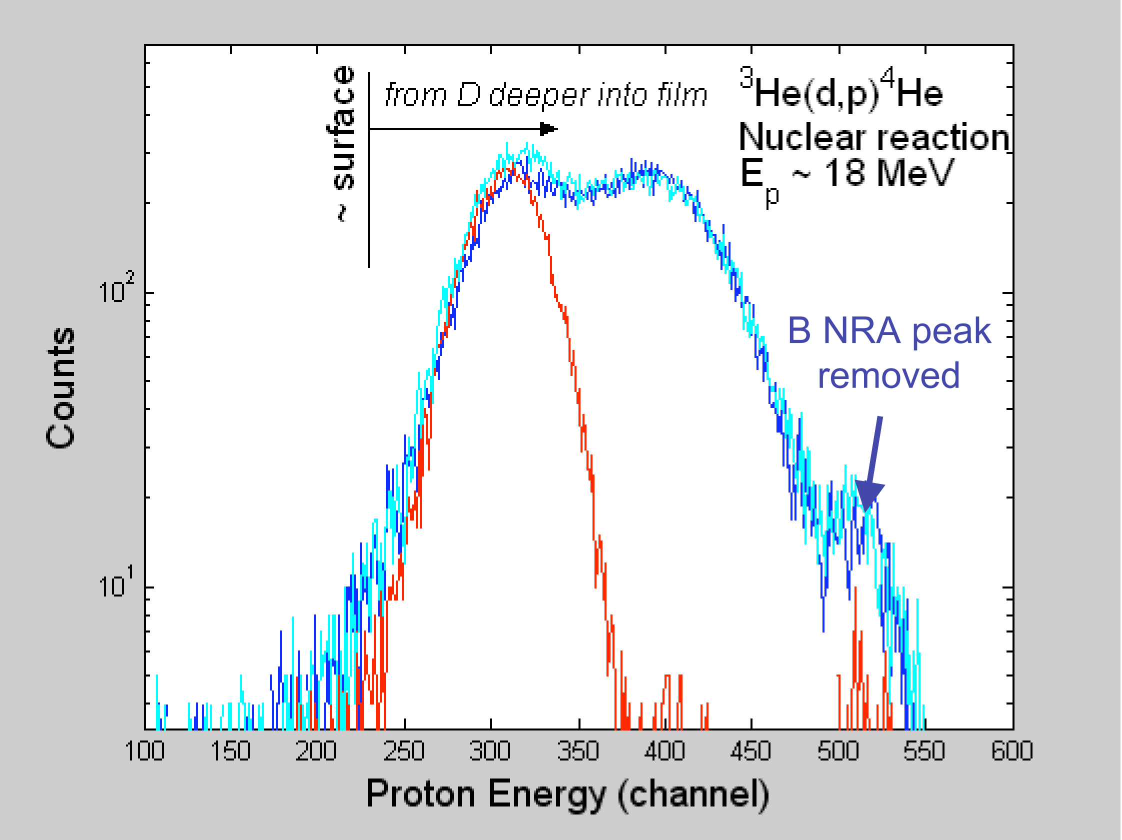
4He beam energy = 3.5 MeV
Forward recoiled H → samples H in~ 1 micron

Deuterium is found through entire depth of the film using 3He Nuclear Reaction Analysis (NRA). Same near surface D concentration after wiping film off with water!

Film removed /w water



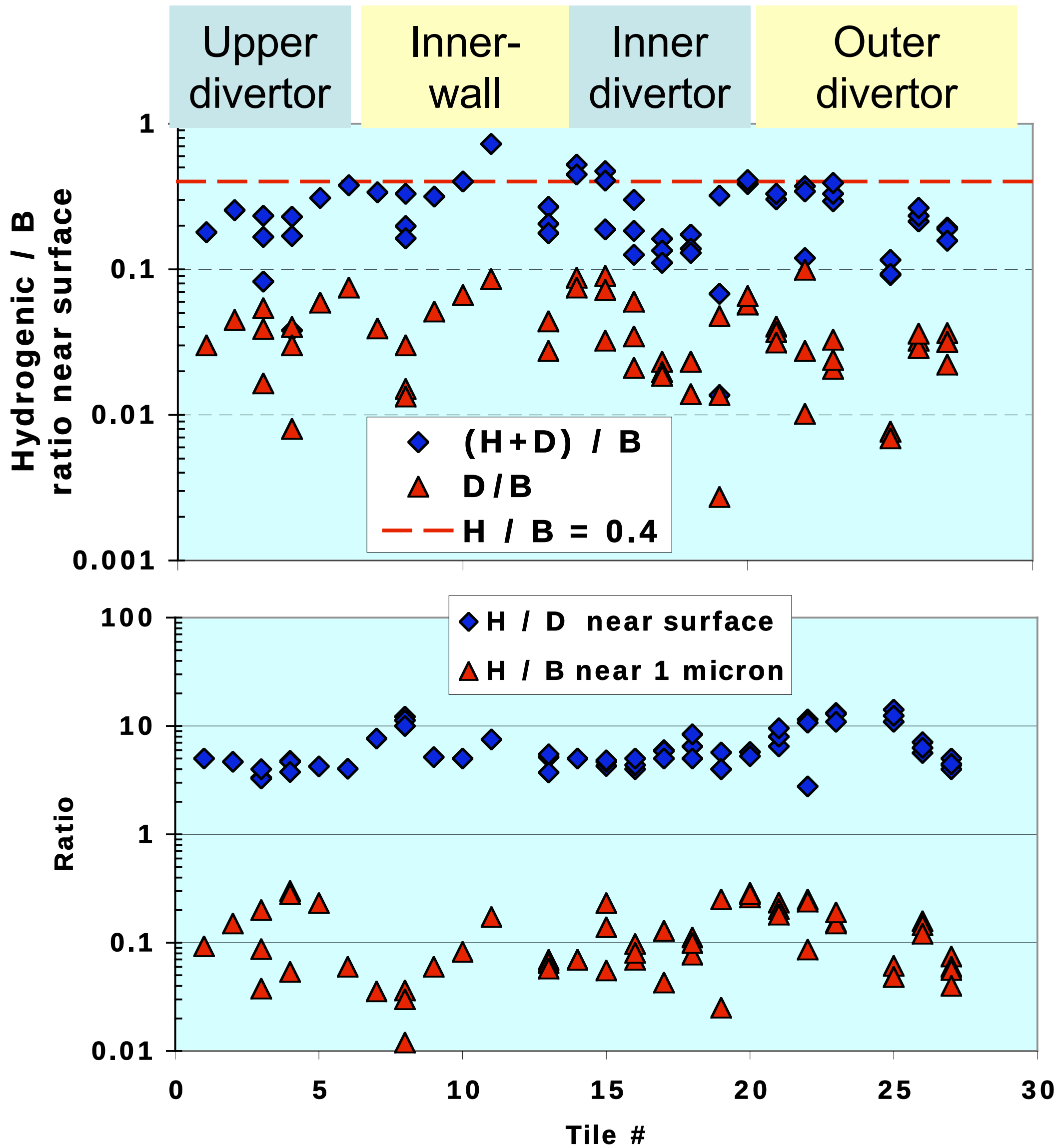
Tile 006C01500
Upper
Midplane at
Inner wall



3He beam energy = 1.5 MeV
Samples D over ~ 1 micron from surface

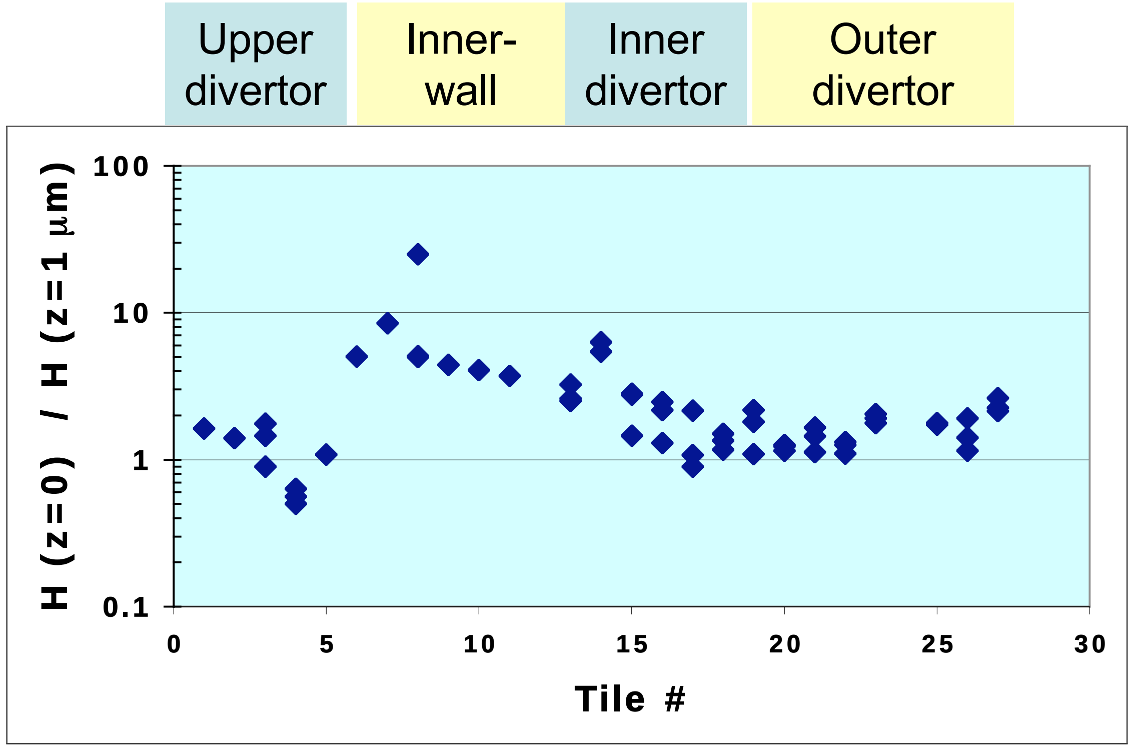
Post-vent fuel inventory in tiles is dominated by hydrogen instead of deuterium. Wall surfaces appear fully saturated with (H+D)/B ~ 0.2-0.4.

- D plasma fueling and deuterated boronizations.
- H presumably arrives from air/H_2O exposure.
- Surface H/D ~5-10.
- Surface (< 1 μm) D / B ~ 0.04 shows scatter with no obvious poloidal pattern.



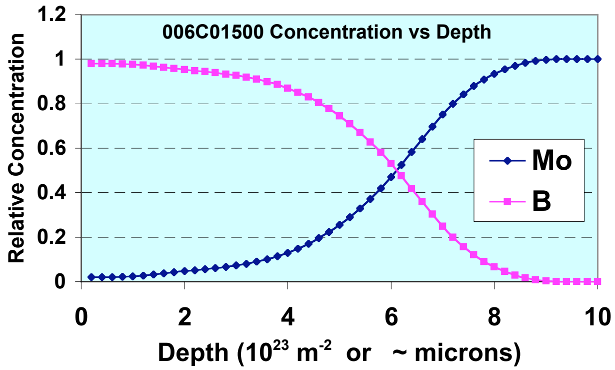
Hydrogen depth profiles vary poloidally, possibly revealing isotope exchange mechanism.

- H profiles highly concentrated near surface at main-wall dominated by boronization films.
- H depth profiles quasi-uniform in divertors.
- Probably informs us about H/D isotope exchange mechanisms?

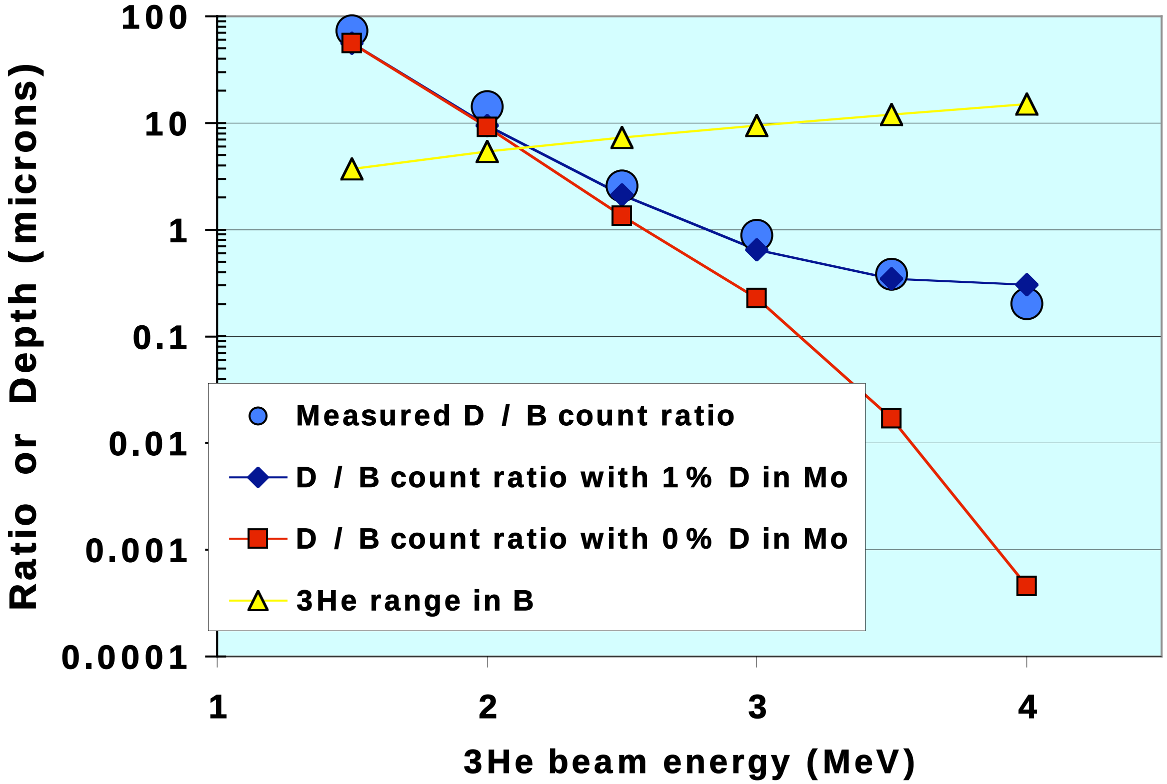


^{3}He(d,p)α NRA depth-profiled deuterium detection indicates constant 1-2% D content through both B and Mo to detection limit of ~ 10 microns.

- RBS shows a ~6 micron B layer on the Mo.



- Increasing ^{3}He energy moves resonance progressively deeper through B and eventually into Mo substrate.



C-Mod tiles provide key insights for operation of high-Z walls & demonstrate the complexity of mixed materials in tokamaks: **Erosion**

- Poloidal distribution of erosion & deposition almost identical to that found in carbon tokamaks → same SOL transport!
  - Outer divertor: net erosion → Inner divertor: net deposition.
  - Consistent with persistent Mach SOL flow (LaBombard APS 04).

- Rate of divertor *net* B erosion/deposition ≤ rates in an L-mode carbon tokamak (DIII-D), ~ 1 nm/s.
  - Divertor ion flux / density x 10 higher in compact high-field C-Mod.
  - Suggests λ_{ion} / R as critical parameter? Implies low net erosion in ITER (REDEP)
  - Rate of global B deposition is externally controlled by boronization.

- Boron has mixed in complicated ways with "substrate" Mo
  - Long-range diffusion of B, despite room temperature operations.
  - No signs of discrete applications of boron, Mo remains at surface.
  - Alloy formation (MoB_2?)

C-Mod tiles provide key insights for operation of high-Z walls & demonstrate the complexity of mixed materials in tokamaks: **H retention**

- C-Mod has hydrogenic saturated walls (H+D) ~ 0.2 - 0.4.

- D and H saturation extends through both B films and Mo.
  - Wiping and ultrasonic cleaning did not change this…filing required!

- Isotope exchange and boronizations make the exact magnitude of codeposition difficult to determine
  - Inner divertor provides codeposition "floor" ~ 2% B/D ratio, with same deposition rate, this results in H/D/T trapping at 1/10th rate of a carbon tokamak (DIII-D).

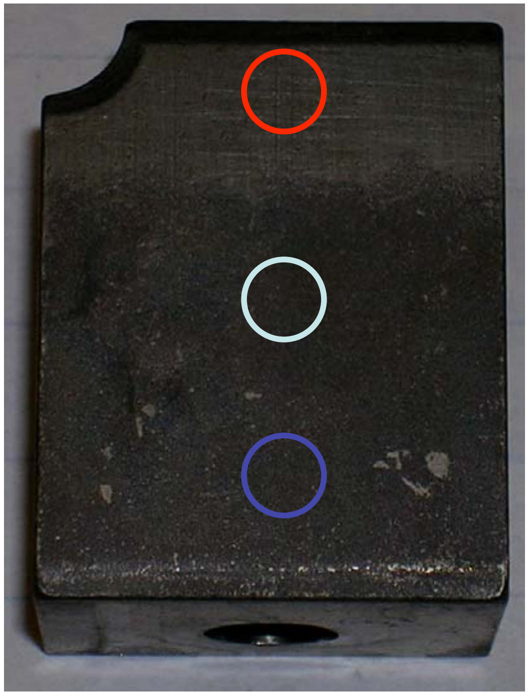
- Hydrogenic isotopic exchange and control seem very important, but exact causes and mechanisms need illumination.

- **As the only all-metal tokamak, C-Mod data is critical in helping us assess Tritium retention in an all-metal ITER.**

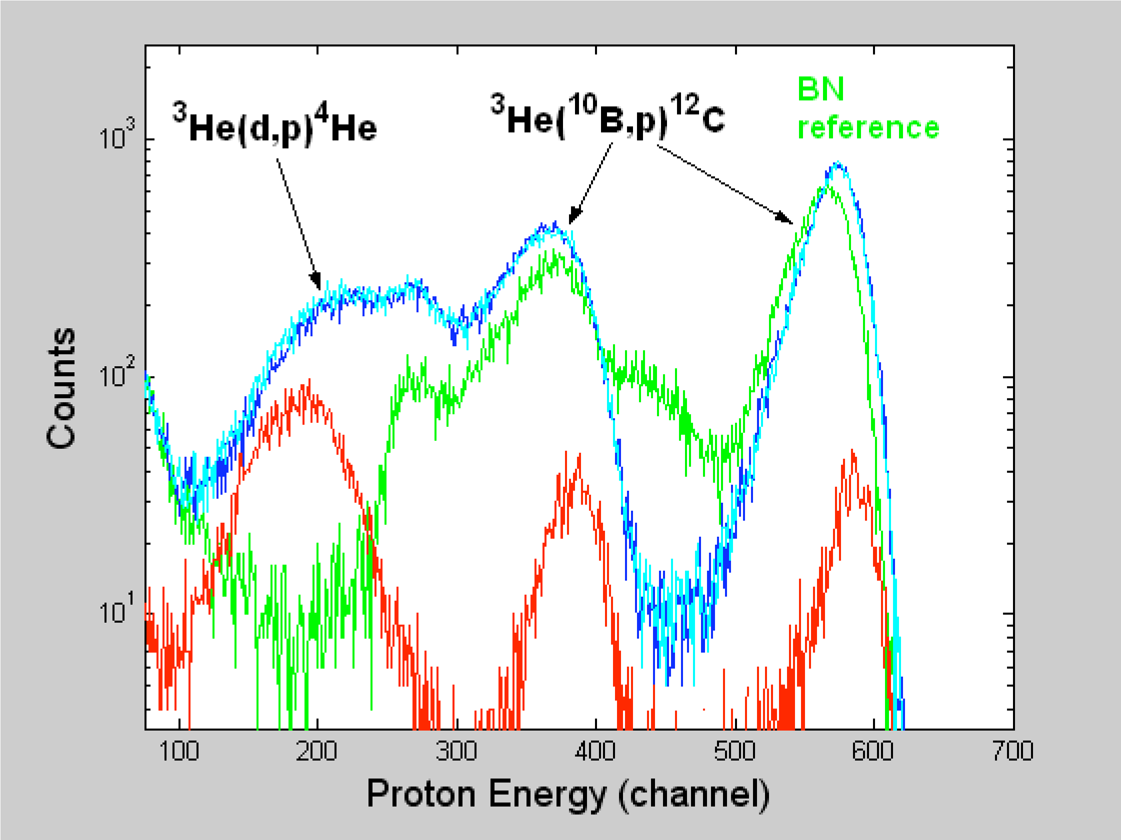
We have begun examining deposition down tile gaps

Deuterium is found through entire depth of the film, Boron NRA shows that surface is essentially pure boron.

Film “wiped” /w water

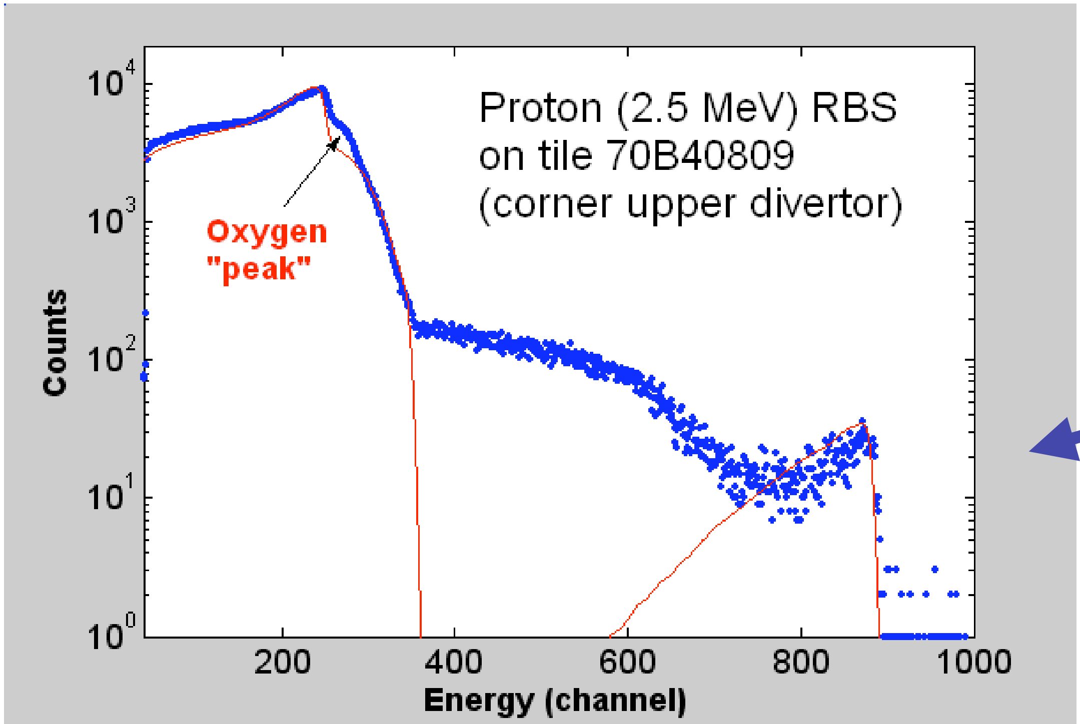


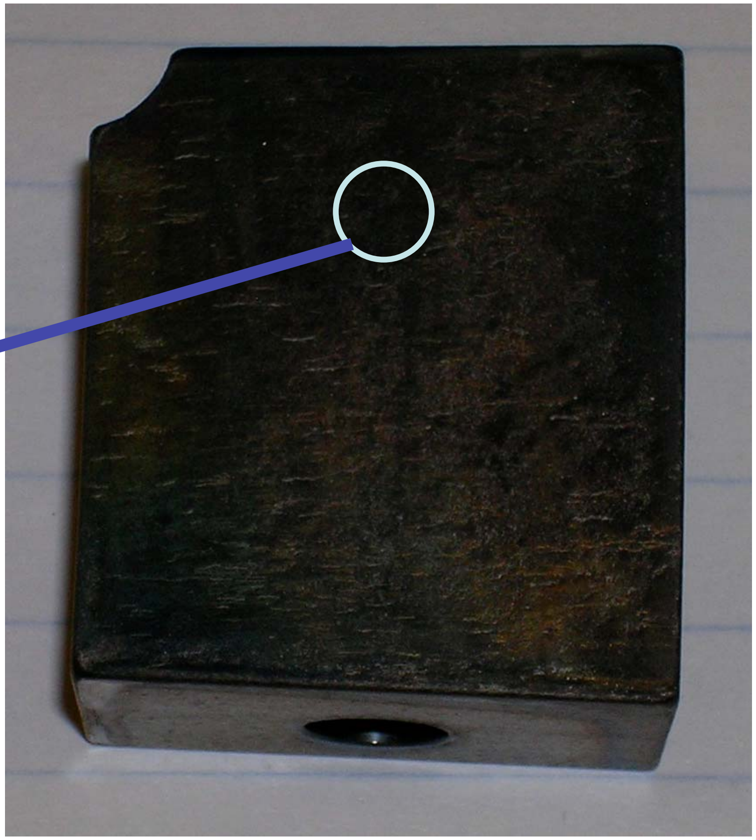
Tile 006C01500
Upper
Midplane at
Inner wall

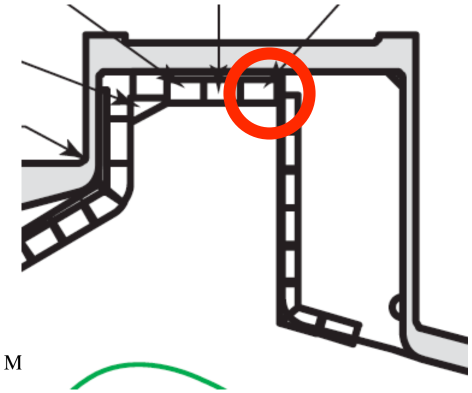


3He beam energy = 3 MeV
Samples D in deeper in film ~ 2-3 microns

In some locations, the boron film is very thick ~10 microns > cumulative boronization layers?
Evidence for oxygen gettering in Boron film.





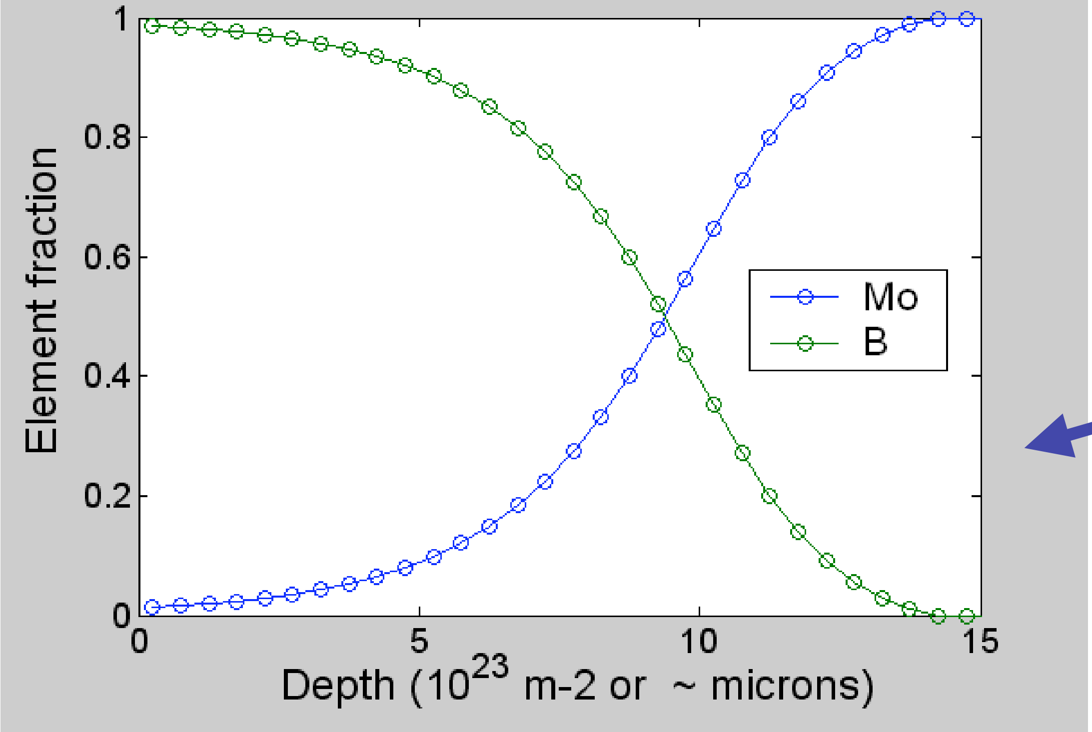


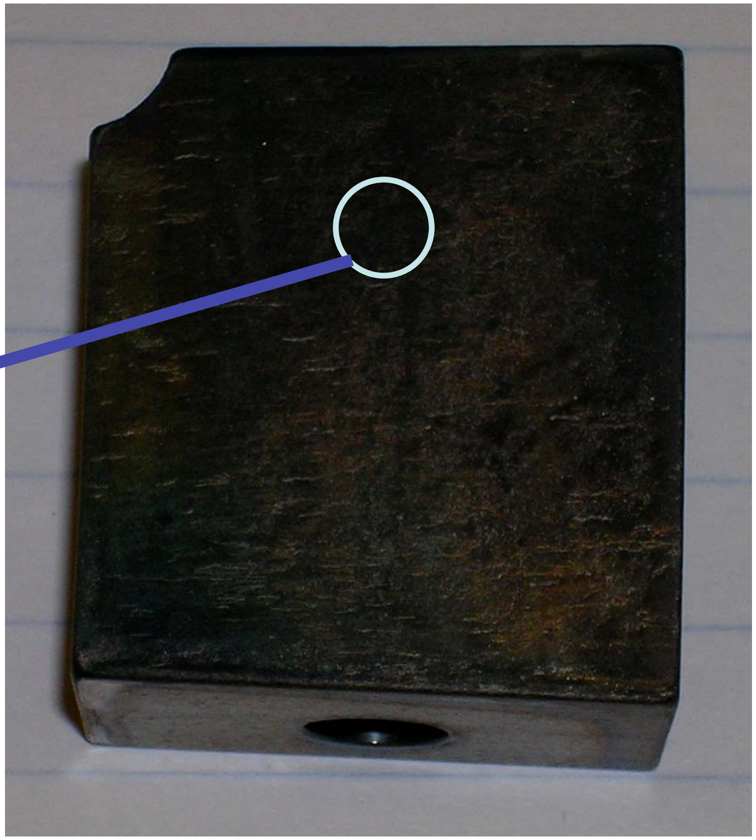
Upper Outer Divertor “corner” tile has brownish appearance and thick B layer

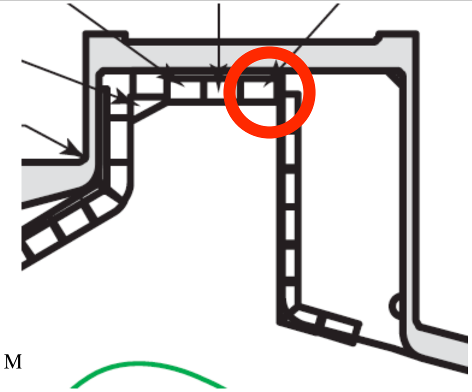
In some locations, the boron film is very thick ~10 microns > cumulative boronization layers?

Evidence for oxygen gettering in Boron film.

Thickest layers at upper divertor (second separatrix?)





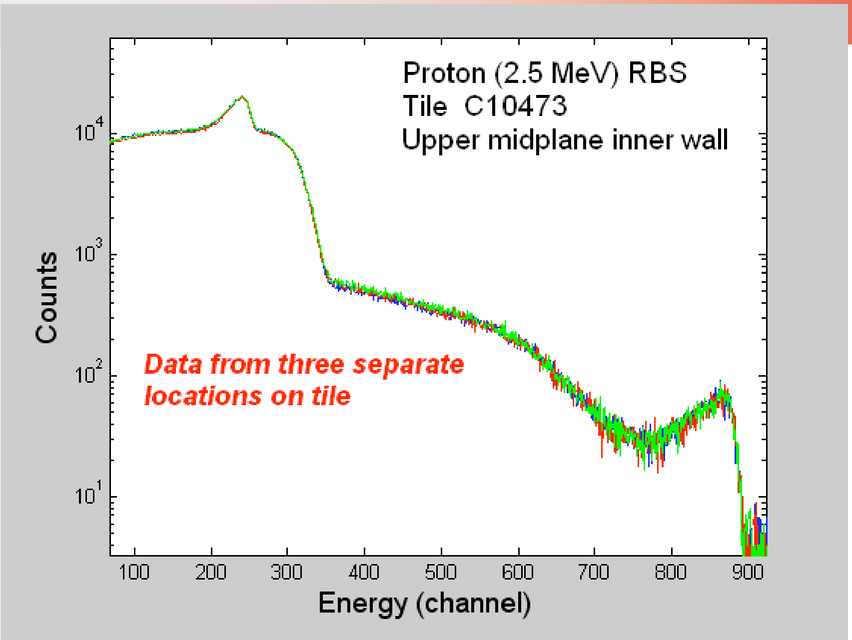


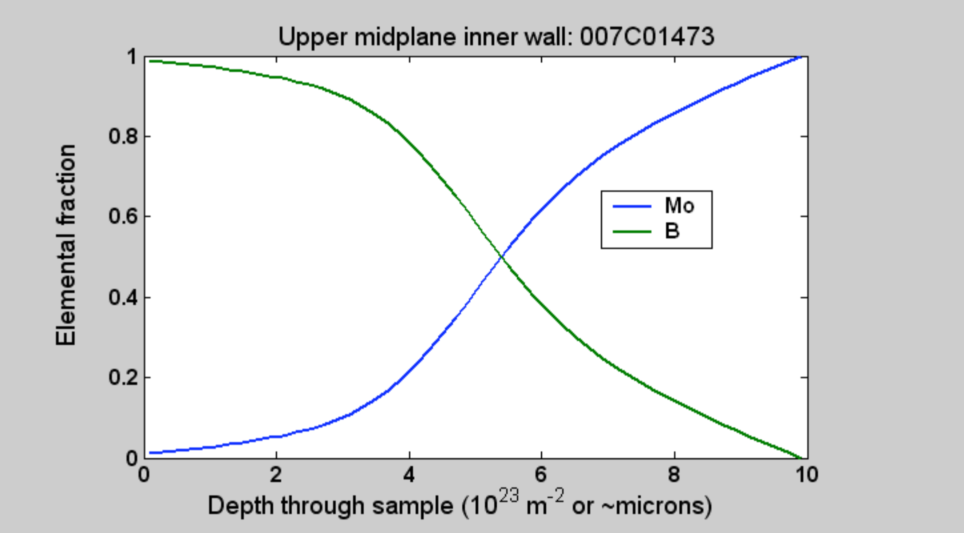
Upper Outer Divertor “corner” tile
has brownish appearance and thick B layer

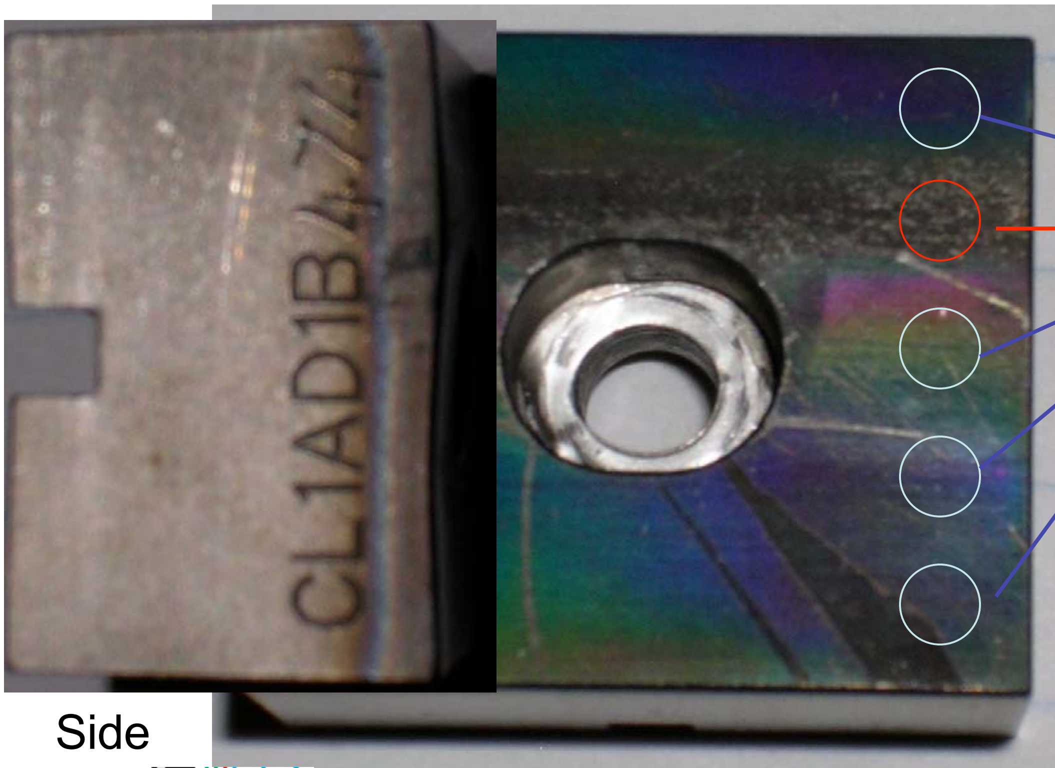
“Non-divertor” tiles typically have spatially uniform B/Mo layers across their plasma-facing surface

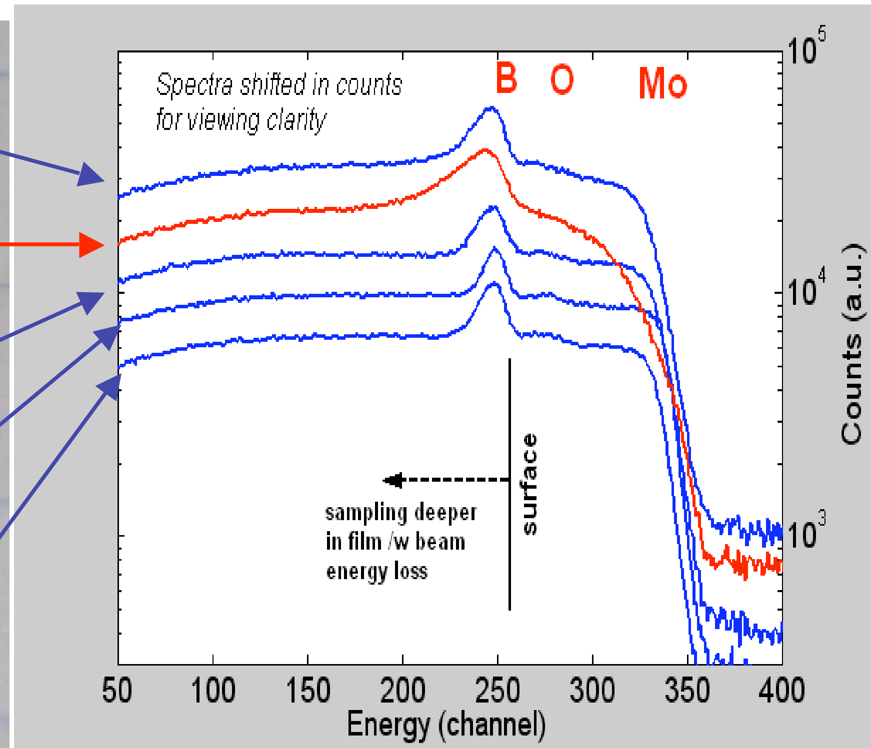
“Wipe” test after measurements

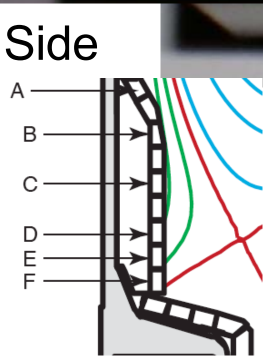
Tile 007C01473
Just above
Midplane at
Inner wall







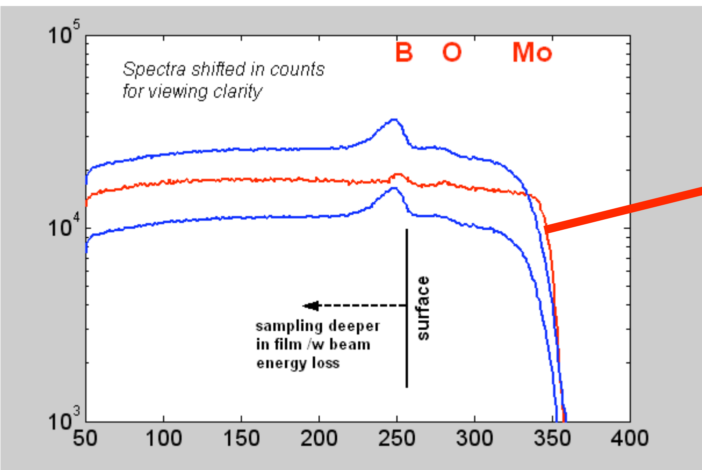


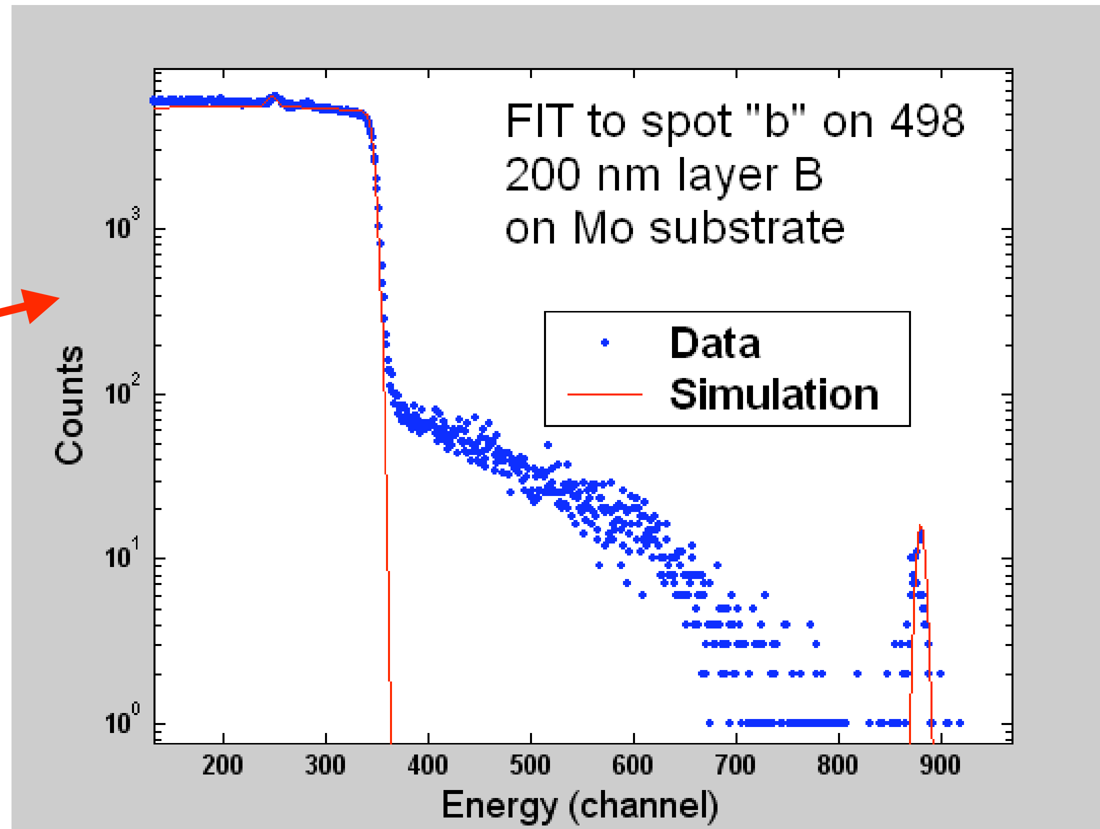


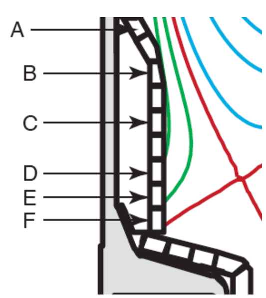
"C" Tile CL1AD1B474: ~ halfway up inner divertor vertical target in "Inner PF region".

Upper trace: Boron half-thickness =1.5 microns

Thinnest boron surface films found on “hidden” slope at inner strikepoint.







“E” Tile CL1AD1B498: ~ Inner Strikepoint.

Middle trace: Boron half-thickness = 0.2 microns